JOURNAL OF MATERIALS SCIENCE 6 (1971) 319–323

Aspects of Stage II Fatigue Crack Propagation in Low-Carbon Steel

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The transition from structure sensitive to structure insensitive Stage II fatigue crack propagation, which has recently been observed in carbon steels, has been studied. The transition crack length is determined by the ratio of plastic zone radius at the crack tip to the grain diameter. An explanation of the transition in terms of constraint at the crack tip is suggested. No systematic change in fatigue crack propagation rate is observed with changes in grain size.

1. Introduction

Fatigue crack propagation, such as occurs from the notch root in a sharply notched fatigue specimen, is referred to as Stage II propagation. Stage I has been reported only in un-notched specimens, in the early stages of cracking. Recent work on the fracture surface topography of Stage II fatigue cracking in low and medium-carbon steels, has indicated that propagation occurs by two distinct modes [1].

The first stage of fracture was microstructure sensitive and has been referred to as Stage IIa propagation. The crack path changed direction at ferrite grain boundaries, revealing the grain structure in the fracture surface. This transgranular structure-sensitive mode was further characterised by markings roughly parallel to the direction of crack propagation, representing a "hill and valley" structure on the fracture surface. At higher magnification, striations could be seen lying in a direction perpendicular to the direction of crack movement. One further feature of the Stage IIa mode of propagation was the presence of a certain amount of intergranular fracture, the proportion of which increased as the carbon content decreased.

The second mode, designated Stage IIb, was insensitive to microstructure and characterised by a more featureless fracture surface with no evidence of the underlying microstructure. Fatigue progression markings (striations) were extremely well defined at this stage of cracking, small undercutting cracks were evident and large branch cracks were also found.

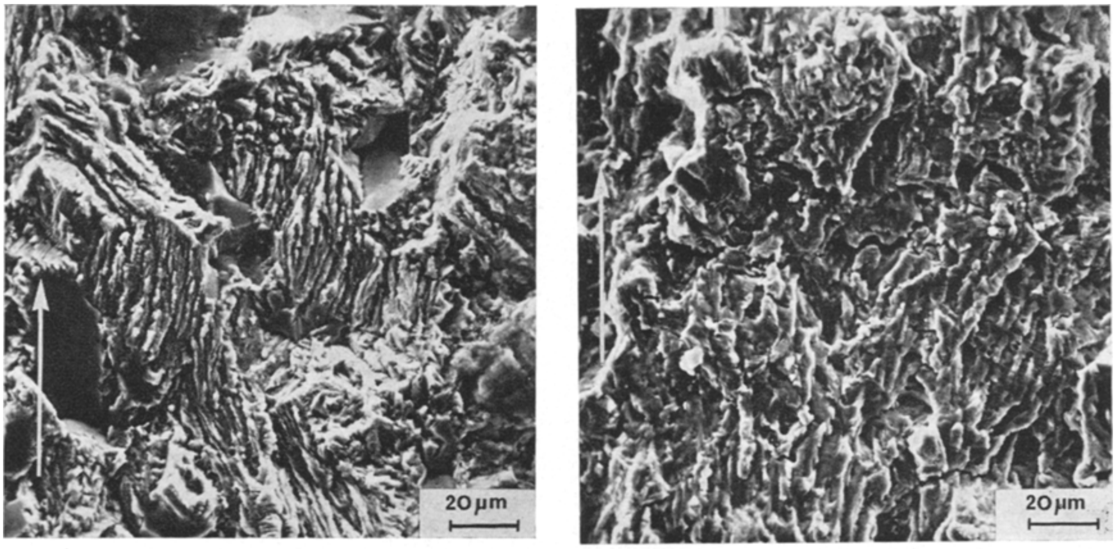
Typical areas of Stage IIa and Stage IIb crack propagation are illustrated in figs. 1a and b respectively.

The present work was undertaken to determine the criterion for the transition from Stage IIa to Stage IIb crack propagation behaviour and to provide an explanation of the effect. The transition crack length has been determined under varying stress conditions at constant ferrite grain size and under varying grain size at constant stress conditions. It is also possible from this approach to evaluate the effect of ferrite grain size on crack propagation rates, both from direct comparison of crack length versus cycles curves and from a fracture mechanics analysis of fatigue crack propagation data.

2. Experimental Procedure

The material used throughout this investigation was a 0.08 carbon, 0.38 manganese, 0.03 silicon (wt %) steel, heat-treated at temperatures in the range of 900 to 1200° C to give a range of ferrite grain sizes from 0.024 to 0.115 mm ($d^{-\frac{1}{2}}$ range of 6.45 to 3.01 $\text{mm}^{-\frac{1}{2}}$). Figs. 2a and b show the general microstructure of the steel at the extremes of the grain size range covered. It should be noted that, although some carbide particles occur at grain boundaries, there is an absence of any extensive grain boundary carbide films.

Using a 2 ton Amsler Vibrophore fatigue machine, fatigue tests were performed on specimens 5.6 × 17.7 × 115 mm with a 1 mm deep notch of 0.05 mm root radius, tested in three-point bend (tension-tension) and push-pull (zero mean stress). Crack lengths were monitored using an optical technique to obtain crack length



(a) (b)

Figure 1 General features of (a) Stage IIa and (b) Stage IIb fatigue crack propagation surface topography in low-carbon steel.

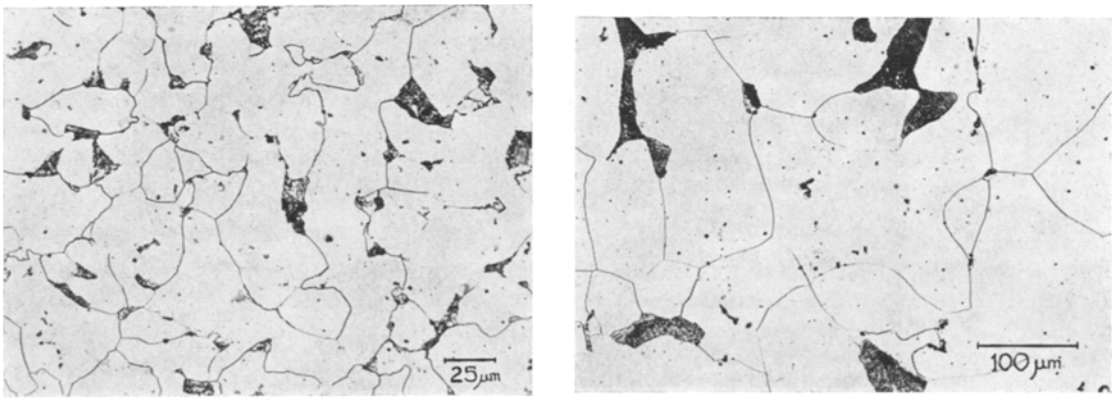
versus cycles curves. The crack length at which the transition from Stage IIa to Stage IIb fatigue crack propagation mode occurred was measured using the micrometer stage of a Cambridge Instruments Stereoscan Scanning Electron Microscope.

3. Results and Discussion

As the fatigue crack propagates under constant load conditions, the stress intensity at the crack tip increases and hence the radius of the plastic zone at the crack tip increases. Assessment of the results obtained showed that the plastic zone size at the tip of the advancing crack and its relationship to grain size of the material, was the controlling factor for the Stage IIa to Stage IIb transition. The plastic zone size for the plane strain conditions prevailing was calculated from the relationship [2],

$$r_y = \frac{1}{5.6\pi}\left(\frac{K_{\max}}{2\sigma_y}\right)^2$$

where r_y is the radius of the plastic zone at $K_{\max}$, the maximum stress intensity at the transition crack length (a_t), and σ_y is the static yield stress (tensile).



(a) (b)

Figure 2 General microstructure of the steel used for fatigue crack propagation studies; (a) ferrite grain size = 0.024 mm and (b) ferrite grain size = 0.115 mm.

TABLE I

Specimen	Grain size (d) 10^{-3} mm	Yield stress kg/mm²	Transition crack length mm	Maximum load kg	Effective pulsating tension stress kg/mm²	K_{crit} kg/mm² $\sqrt{mm}$	Radius of plastic zone mm(r_y)	Ratio r_y/d
TR1	99.8	11.92	1.852	350		60.3	0.363	3.6
TR2	114.9	11.75	2.173	350		64.7	0.429	3.8
TR3	74.1	12.57	1.704	350		60.0	0.323	4.4
TR4	72.5	13.61	2.080	350		63.2	0.307	4.2
TR5	72.1	13.61	2.300	350		66.5	0.340	4.7
TR6	67.0	13.78	1.995	350		63.1	0.297	4.4
77a	24.7	18.11	0.725	350		48.7	0.103	4.2
77b	24.7	18.11	0.719	350		48.5	0.102	4.1
67a	24.7	18.11	0.157	406		47.2	0.097	3.9
67b	24.7	18.11	0.232	406		48.5	0.102	4.1
83a	24.7	18.11	1.334	309		49.0	0.104	4.2
83b	24.7	18.11	1.065	309		46.4	0.093	3.8
Z1	24.7	18.11	1.172		14.11	44.9	0.086	3.6
Z2	24.7	18.11	1.455		14.11	49.7	0.107	4.3
Z3	24.7	18.11	2.579		10.10	46.6	0.094	3.8
Z4	24.7	18.11	2.839		10.10	49.0	0.104	4.2
Z5	24.7	18.11	3.607		7.67	44.8	0.086	3.5
Z6	24.7	18.11	3.780		7.67	46.6	0.094	3.8

Table I gives calculated values of the plastic zone radius and the ratio of plastic zone radius to the ferrite grain diameter, at the crack length for the Stage IIa to Stage IIb fatigue crack propagation transition. For the zero mean stress tests, the effective pulsating tension stress, calculated from work by Gurney [3], was used to calculate the maximum stress intensity at the transition crack length. Two important points emerge from a consideration of the data in table I. Firstly, it can be seen that at constant grain size, there is a critical value of stress intensity ($K_{crit} \simeq 48$ kg mm$^{-3/2}$) and hence a specific plastic zone size, at which the transition occurs. This value of the stress intensity factor remains constant with changes in alternating load level, in tension-tension tests, and under zero mean stress conditions. Secondly, for this material over the grain size range covered, the ratio of plastic zone radius to grain diameter at the Stage IIa to Stage IIb fatigue crack propagation transition is constant at about four. The range of values of the ratio stated in table I (3.5 to 4.5) is probably due to inaccuracies in determining the crack length at the transition.

This type of behaviour suggests that when the plastic zone is small, extending over only one or two grains ahead of the crack tip, constraint is high and a restricted number of slip systems are available. This causes specific planes in the ferrite to fracture, giving rise to a "hill and valley" structure (fig. 3) across which progression markings are formed. Under these conditions, cracking will also occur along favourably orientated grain boundaries (fig. 4). Fig. 4 also shows surface effects produced on the intergranular facets which indicate that slip may then occur in these grains after the passage of the crack tip.

It is unlikely that the intergranular facets are associated with grain boundary carbide films, since the amount of grain boundary carbide is extremely small, and in no case were grain boundary carbides detected on the fracture surface. Also, intergranular facets in Stage IIa mode propagation have been observed in high purity fcc metals where no grain boundary embrittling phases are present [4].

As the plastic zone increases in radius, beyond about four grains ahead of the crack tip, the degree of constraint is reduced, much more slip can occur due to increased grain boundary slip compatibility, and the crack begins to propagate in a much larger pre-deformed zone. As a result of this, the fracture became much less sensitive to structure (less crystallographic) and the degree of constraint was so reduced as to provide conditions not conducive to grain boundary fracture.

It is noticeable from observations of typical crack length versus cycles curves in fig. 5, that no

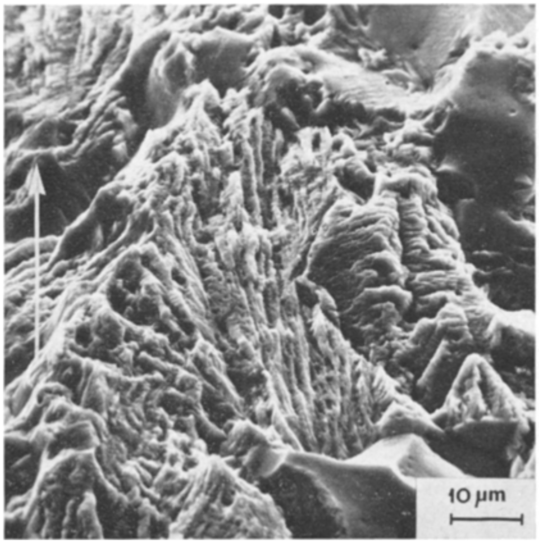


Figure 3 Transgranular "hill and valley" structure of Stage IIa fatigue crack propagation.

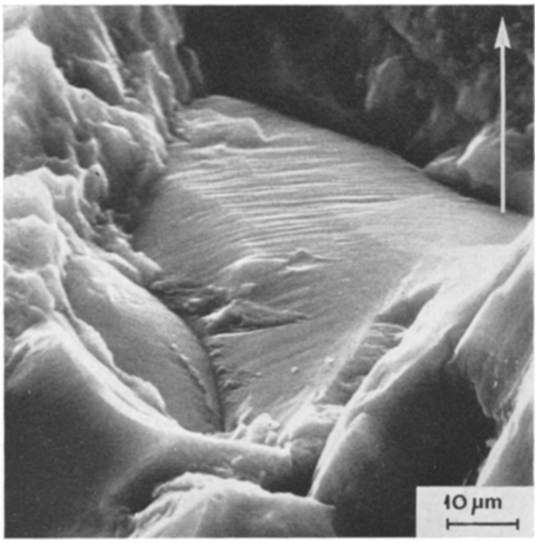


Figure 4 Intergranular facet, showing surface slip effects, in Stage IIa region of fatigue crack growth.

distinct change in propagation rate occurred at the transition from Stage IIa to Stage IIb propagation.

Assessment of fatigue crack propagation rates in specimens of varying grain size according to the relationship [5],

$$\frac{da}{dN} = C(\Delta K)^m$$

where da/dN is the crack propagation rate, ΔK is the stress intensity range and C and m are material constants, indicates that no consistent change in fatigue crack propagation rate occurs with changes in grain size (table II). It should be noted however, that the fracture mechanics analysis of fatigue crack propagation data used here is extremely insensitive to microstructural effects. McEvily and Johnston [6] have shown that even if the analysis is modified to incorporate the effects of strain-hardening, yield strength (and hence grain size) and tensile strength, the effects produced by substantial increases in properties (say by changing grain size) are still second order. Indeed, the magnitude of the

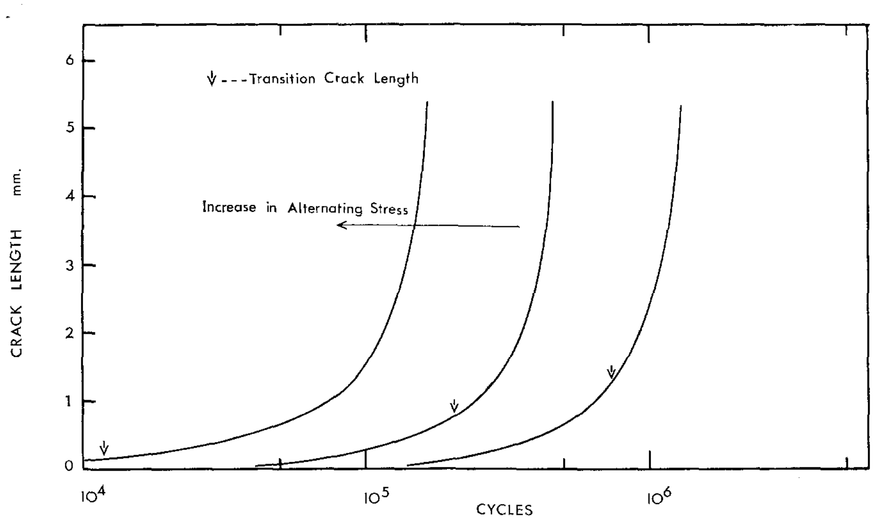


Figure 5 Crack length versus cycles curves at various alternating load levels.

TABLE II

Specimen	Grain size 10^{-3} mm	m	C
TR2	114.9	2.63	5.01×10^{-18}
TR3	74.1	2.91	3.16×10^{-18}
TR4	72.5	2.84	6.31×10^{-19}
TR5	72.1	2.49	1.58×10^{-17}
TR6	67.0	2.69	2.51×10^{-18}
67a	24.7	2.81	7.94×10^{-19}
77a	24.7	2.81	7.94×10^{-19}

change expected in C and m from this analysis is within the scatter of the present data.

4. Conclusions

4.1

At constant grain size, a transition from structure sensitive (Stage IIa) to structure insensitive (Stage IIb) fatigue crack propagation occurs at a critical value of stress intensity independent of mean stress and stress amplitude.

4.2

Under constant stress conditions with variable grain size, and constant grain size with variable stress conditions, the transition from Stage IIa and Stage IIb occurs when the ratio of plastic zone radius to ferrite grain diameter is approximately four.

4.3

The transition is thought to be due to the relaxation of constraint at the crack tip as the crack length increases.

4.4

No systematic change in crack propagation behaviour, expressed as the C and m values from the fracture mechanics analysis of fatigue data, is observed with changes in ferrite grain size, under constant loading conditions.

Acknowledgement

The authors are grateful to the British Railways Board for permission to publish this paper.

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Received 8 September and accepted 11 January 1971.